Critical current density and ac harmonic voltage generation in YBa$_2$Cu$_3$O$_{7-\delta}$ thin films by the screening technique.

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Abstract

The temperature and field dependence of harmonics in voltage $V_n = V_n' - iV_n''$ using the screening technique have been measured for YBa$_2$Cu$_3$O$_{7-\delta}$ superconducting thin films. Using the Sun model we obtained the curves for the temperature-dependent critical current density $J_c(T)$. In addition, we applied the criterion proposed by Acosta et al. to compute $J_c(T)$. Also, we made used of the empirical law $J_c \propto (1 - T/T_c)^n$ as an input in our calculations to reproduce experimental harmonic generation up to the fifth harmonic. We found that most models fit well the fundamental voltage but higher harmonics are poorly reproduced. Such behavior suggests the idea that higher harmonics contain information concerning complex processes like flux creep or thermally assisted flux flow.

Key words: Critical current; Screening technique; flux pinning; thin films
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1. Introduction

In this contribution we shall determine the temperature dependence of the critical current density $J_c(T)$ for YBa$_2$Cu$_3$O$_{7-\delta}$ thin films by measuring the harmonics of voltage $V_n = V_n' - iV_n''$ ($n = 1, 3, 5...$) with the screening technique [1]. The calculation is based on the Sun model [2] and the definition of the full penetration field H_p from the critical-state model [3] . Also an extension to higher harmonics of the this model shall be worked out and compared with experimental curves.

2. The Sun Model and Experimental

We have determined the harmonics of voltage V_n based on the theoretical approach developed by Sun et al. [2]. He proposed a model to compute the ac susceptibility response of thin-film superconductors under the influence of a transversal ac magnetic field $H_a = H_{ac}\sin(\omega t)$. In response to H_a shielding currents $\mathbf{J}_c$ induce a diamagnetic moment which Sun et al. found to be

$$m^{\pm}(H_a) = \pm \frac{H_p a^3}{2}\left[\exp\left(-\frac{H_{ac} \pm H_a}{H_p}\right) - \left(\frac{1}{2} + \eta\right)\right] \quad (1)$$

where $\eta = 1/2 \exp(2H_{ac}/H_p)$ and a is the radius of the film. The full penetration field stems from the Bean result, namely $H_p = J_c d/3$, where d is the film thickness. Actually the quantity to be measured is the volt-

age $V(t)$ induced in the pick-up coil, which is conventionally measured with a lock-in amplifier and is proportional to dm/dt. The voltage can be expanded as a Fourier series: $V(t) = \sum_{n=1}^{\infty}[V_n'\cos(n\omega t) + V_n''\sin(n\omega t)]$, where $V_n' = \frac{1}{2\pi}\int_0^{2\pi} V(t)\cos(n\omega t)d(\omega t) \propto H_{ac}\omega\chi_n'$, and $V_n'' = \frac{1}{2\pi}\int_0^{2\pi} V(t)\sin(n\omega t)d(\omega t) \propto H_{ac}\omega\chi_n''$ stands for the real and imaginary components of voltage, respectively, χ_n is the magnetic susceptibility. Here we shall deal with harmonics with $n = 3, 5$. The fundamental harmonic can be found elsewhere [2]. The solutions for the real part read:

$$V_3' = -\frac{6m_0 e^{-h}}{h}\left[4I_2(h) - hI_1(h)\right], \quad (2)$$

$$V_5' = -\frac{10m_0 e^{-h}}{h^2}\left[48I_3(h) - 12I_2(h) + h^2I_1(h)\right],$$

where $m_0 = 2\pi J_c da^3/3$ and $h = H_a/H_p$ is the reduced field, the functions $I_\nu(h)$ (with $\nu = 1, 2, 3$) are the modified Bessel functions. The imaginary components are

$$V_3'' = f(h)(3S_1 - 4S_2),$$
$$V_5'' = f(h)(5S_1 - 20S_2 + 16S_3), \quad (3)$$

where $f(h) = -2m_0 he^{-h}/\pi$ and the functions S_n are given by

$$S_1 = -\frac{2}{h^2}\left\{h\cosh(h) - \sinh(h)\right\}, \quad (4)$$

$$S_2 = -\frac{2}{h^2}\left\{h\cosh(h) - 3\left[S_1 + \sinh(h)\right]\right\},$$
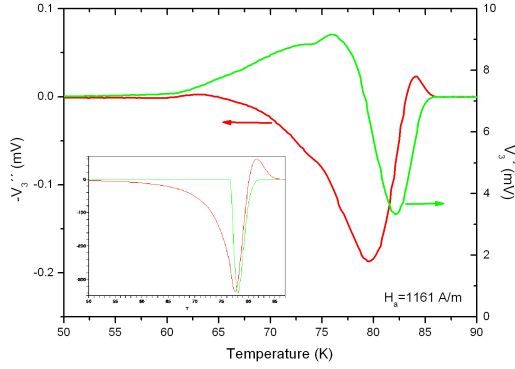
$$S_3 = -\frac{2}{h^2}\left\{h\cosh(h) - 5\sinh(h) - 10S_2\right\}.$$

Figure 1: Temperature-dependence of real and imaginary part of the third harmonic. Inset shows theoretical curves.
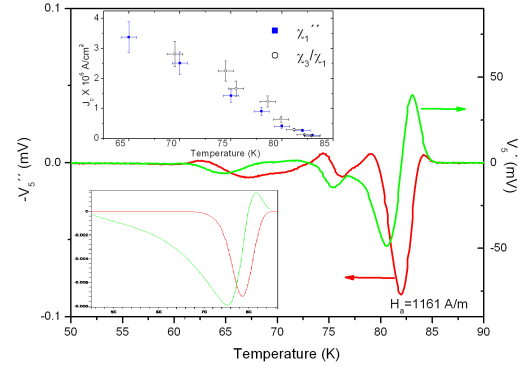

Figure 2: Temperature-dependence of real and imaginary part of the fifth harmonic. Bottom inset shows theoretical curves. Top inset shows the curves for the $J_c(T)$.

To determine the critical current density $J_c(T)$ we have taken into account the criterion proposed by Acosta et al. [4]. He proposed that H_p is the value associated with the highest peak in the ratio $\chi_3(H_{ac})/\chi_1(H_{ac})_{max}$. We also add the criterion of Xing et al. [5], based on the measurement of the maximum of $\chi_1''(T)$. Under this method the critical current density is found to be $J_c(T_p) = 3.157 H_a/d$, where T_p is the temperature at the peak. These quantities are reported in SI units. Measurements of harmonics in voltage using the screening [1] technique were carried out on superconducting thin films of $YB_2C_3O_{7-\delta}$ with a $T_c = 86.5$ K. We applied a transverse H_{ac} field whose amplitude could vary from 0 to 5000 A/m with a fixed frequency of 1 KHz. For the ratio χ_3/χ_1 we have realized 11 different plots each corresponding to the temperatures: 20, 35, 45, 55, 65, 70, 75, 78, 80, 82 and 83 K. On the other hand, the temperature-dependence of the imaginary component of the fundamental harmonic was realized for 8 different field amplitudes i.e., H_a =77, 118, 277, 690, 1161, 1836, 2315, 2665 A/m rms.

3. Results and Discussion

The upper inset in Fig. 2 shows the curves for the $J_c(T)$ with a systematic uncertainty of 20%. Within the estimated uncertainties both the χ_3/χ_1 and the χ_1'' approaches lay in the same order of magnitude. Therefore we conclude that in fact both approaches are equivalent.

Taking as an input, in Eqs. 2 and 3, the empirical law $J_c(T) = k(1-t)^n$ where $t = T/T_c$ is the reduced temperature, and k and n are experimental parameters we have plotted the harmonics of voltaje. We found that in the high temperature region curves are well fitted with $n = 3.4$ and $k = 6.5 \times 10^7$ and for lower temperatures the values $n = 2.8$ and $k = 3.5 \times 10^7$ fit well. In Figs. 1 and 2 we plot both the measured and computed curves for the third and fifth harmonics, respectively. In the real part of the third harmonic the theory can not account for the

positive peak. On the other hand, the imaginary part is qualitatively well described. The computed values for the fifth harmonic does not account for the oscillatory behavior on the left of the main peaks. As temperature goes down from above T_c the main peaks agree with the theory but as the system further cools, some new features appear that suggest the presence of other mechanisms than pinning. The overall behavior for harmonics higher than the first proposes not only that pinning is the only mechanism implied in the dynamics of fluxons but also that thermally assisted flux flow (TAFF) and flux creep are present. Also a field-dependence of $J_c(B)$ is not accounted for in the model and it may be found in harmonics higher than the fundamental. However, S. Shatz et al. [6] have shown that the Kim-Anderson model with $J_c = J_c(B)$ also yields a universal behavior in the curves which in consequence does not produce the additional peaks. This fact has the importance conclusion: that the observed peaks must be caused only by thermal effects as the transition occurs.

Acknowledgements

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